



# RESPONSE OF BUILDING COMPONENTS TO LAUNCH ACOUSTIC ENVIRONMENT

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A computational procedure is presented for calculating the response of building components to acoustic loads due to spacecraft launch. The methodology described is in-built as routines into a software module “ACOUP” which forms part of the OSTA software package for off-shore and on-shore structural analysis using finite elements [1]. The software developed can be used to predict the acoustic response of any structure/structural component. One wall panel and one roof panel in each of the two buildings in launch acoustic environment at SHAR, INDIA and KSC, U.S.A. are analysed and the computed acoustic responses are compared with the responses measured at the respective places during the launches.

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## 1. INTRODUCTION

The structures located in a spacecraft launch complex experience intense dynamic loading during the launching of spacecrafts. With the continuous developments in the space programs, high-powered rocket boosters are being used to launch satellites of greater pay load capacities. As rocket booster thrust continuously increases, the design and evaluation efforts required for the solution of the dynamic effects due to acoustic loading are intensified. Given the rapid pace of development in rocket boosters and in the interest in a manned space station, the space shuttles in future may be replaced by more powerful launching vehicles. The acoustic pressures produced from these future rocket engines may be more intense and their effects on structures more pronounced. Since the structures located in a launch complex house essential equipment, these structures have to be protected from any

damage which in turn could adversely affect future launches. Hence, there is a need for effective methods for characterizing the pressure wave and generating design and evaluation data.

Towards achieving this objective, the authors have conducted field investigations on acoustic pressures and structural responses during several rocket launches [2–4] and have evolved an empirical model for the acoustic pressure spectrum. Wills *et al.* [5, 6] collected and analysed acoustic pressures and structural responses from the transducers mounted on the roof and walls of a building called Switching Station Enclosure (SSE) building, approximately 105 m west of launch pad 39A at Kennedy Space Centre (KSC), U.S.A. The results obtained by the above experiments are compared with the results obtained by the computational procedure presented in this paper.

## 2. ACOUSTIC RESPONSES OF BUILDINGS

Acoustic loading is due to spatially varying and frequency-dependent sound pressure fluctuations on the surface of the structures. For the service structures near the launch pad, they are considered as random loads, broad-banded in nature with significant frequency range of 0–300 Hz and transient in nature, lasting only about 6–8 ss.

### 2.1. EXPERIMENTAL INVESTIGATIONS

Several buildings in the SHAR complex located near the launch pad have been instrumented with acoustic sound pressure level gauges (Figure 1). Figure 2 shows

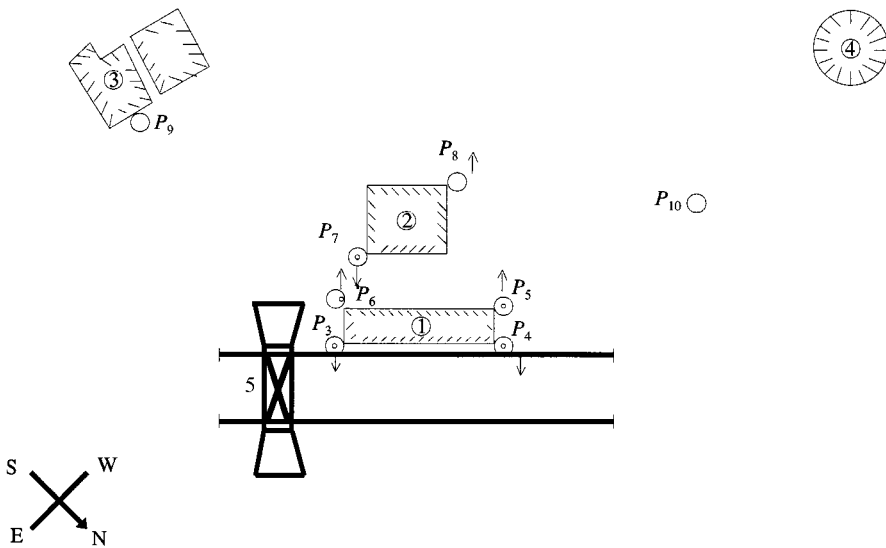


Figure 1. Location of sound pressure level gauges (SHAR-India). ● SPL Gauge locations; 1. C.T.R Building; 2. C.G.S.S Building; 3. LH2 Building; 4. O.H.R Water tank; 5. Launch pad.

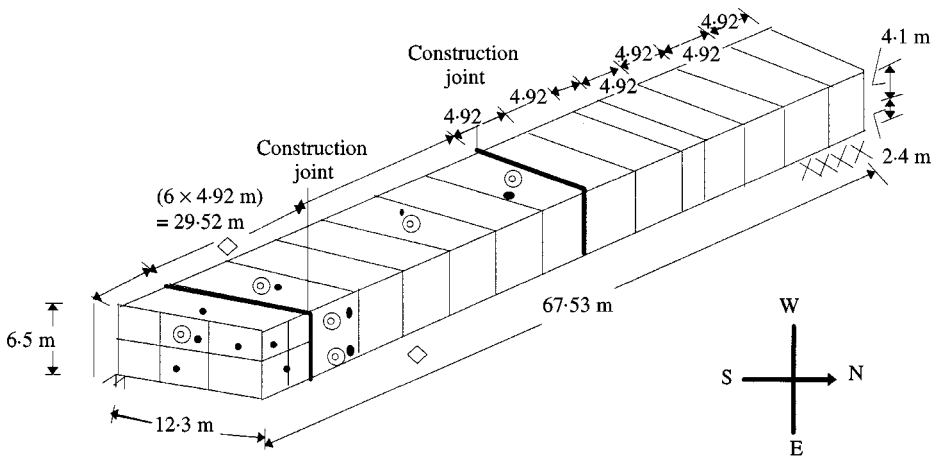


Figure 2. Location of accelerometers and strain gauges on CTR building (SHAR-India). ◇, Ground accelerometers; ●, strain gauges; ⊙, accelerometers.

the location of accelerometers and strain gauges installed in the Checkout Terminal Room (CTR) building.

The sound pressure levels measured during the PSLV-D3 launch have been analysed, and based on this analysis it has been concluded that the peak acoustic pressure at ground level decays approximately as the square of distance from the launch pad [7]. The structural response data measured during the PSLV-D3 launch have also been analysed and these results are being used in the present paper to compare with the predicted structural responses using the computational methodology suggested in this paper.

The Switching Station Enclosure (SSE) building at Kennedy Space Centre (KSC), U.S.A., is composed of prestressed concrete double tee roof and wall panels. Figure 3 shows the SSE building and typical roof and wall panel details. Figure 4 shows the location of transducers on this building during STS-48 launch.

## 2.2. ANALYTICAL INVESTIGATIONS

Lin [6] has analysed the Switching Station Enclosure building in the KSC launch environment for acoustic response. The acoustic pressure is varied in magnitude by Lin [6], over different building components, in a series of trials, so as to achieve better comparison with the measured responses. The pressure loading on the north wall and roof panels is assumed to be the same as that measured. Doubled pressure loading is applied on the south wall panels and four times the pressure loading is applied on east wall panels. Damping factor is assumed constant for all modes as 0.03.

This building is modelled by Lin [6] using I-DEAS finite element modelling software. MSC/NASTRAN software is used to predict the eigenvalues, eigenvectors and power spectral densities of acceleration response to measured

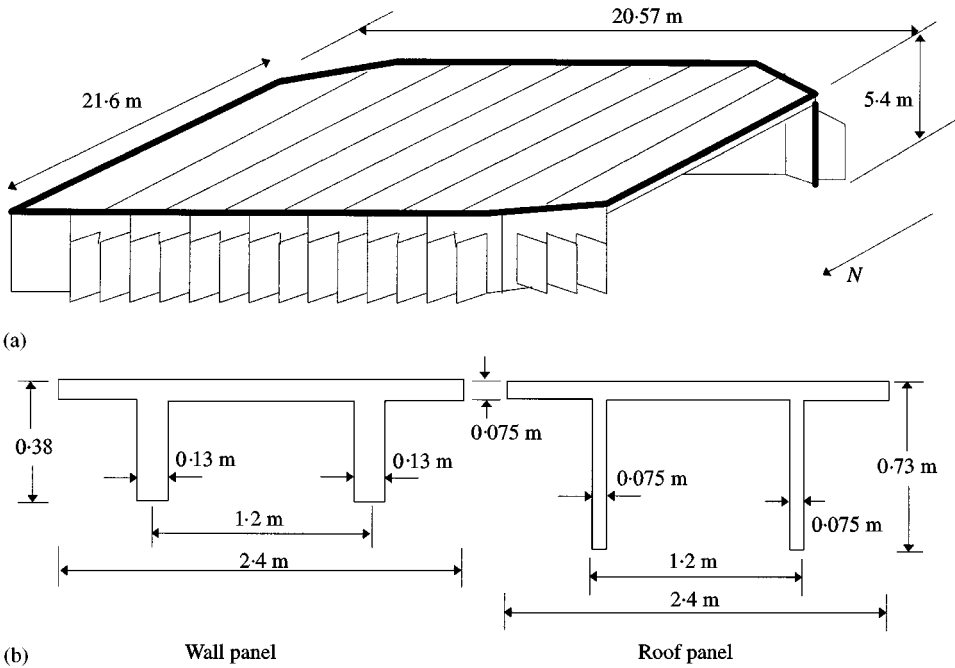


Figure 3. (a) Switching station enclosure building; (b) details of typical wall and roof panels (KSC-U.S.A.) (Note: figure not to scale).

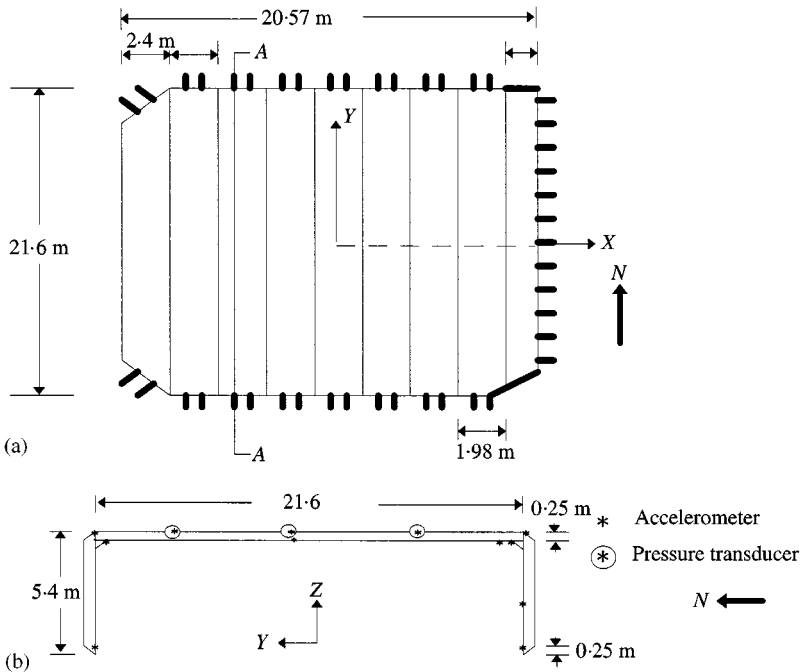


Figure 4. (a) Location of transducers on SSE building (plan); (b) Location of transducers on SSE building (KSC-U.S.A.)

acoustic pressures. These theoretical and experimental results are being compared in the present paper with the responses predicted for the same building components using ACOUP software, developed by the authors.

### 3. METHODOLOGY FOR COMPUTING ACOUSTIC RESPONSE

In a launch environment, the exterior elements of a building receive the acoustic pressure and transfer the load to the rest of the structure. Hence, the primary task is to determine the elemental acoustic loads and then transfer these loads on to the nodes of these elements. For an element  $m$ , in a structure, the acoustic loading is computed as follows.

The acoustic force on element,  $m$  at time  $t$  is

$$F_m(t) = P_m(t)A_m, \quad (1)$$

where  $P_m(t)$  is the acoustic pressure at the centre of the element and  $A_m$  the area of the element  $m$ .

The acoustic pressure varies with time and no definite relationship exists to describe the random variation of the pressure.

Figure 5 shows a typical acoustic pressure time history collected during the PSLV-D3 launch at SHAR centre, India.

The computation of the stochastic response of structures subjected to acoustic loading has to be carried out in the frequency domain so as to avoid a prohibitive extent of computational effort required for temporal or time domain approach. The spectral approach, which seeks solution at a few discrete frequency steps, involves only a few matrix operations. In this paper, the acoustic response evaluation is based on a normal mode approach very well described in the literature and is followed by many [8–10]. However, the difficulty arises in modelling the PSD of

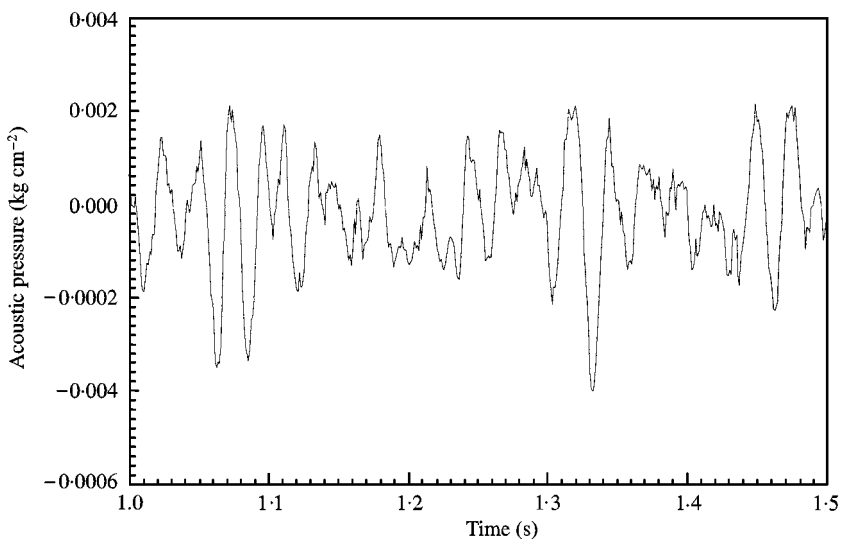


Figure 5. Typical acoustic pressure time history.

the acoustic pressure on a finite element model. The contribution of this paper is, essentially, the development of such a model, based on field data.

The acoustic force on element  $m$  can be written in the frequency domain as

$$S_{fm}(\omega) = S_{pm}(\omega)A_m^2, \quad (2)$$

where  $S_{fm}(\omega)$  is the PSD of force acting on element  $m$  and  $S_{pm}(\omega)$  is the PSD of pressure acting at the centre of element  $m$ .

The task of predicting the acoustic response can, therefore, be carried out only if there is an acceptable formula for  $S_{pm}(\omega)$ .

### 3.1. FORMULATION OF THE POWER SPECTRAL DENSITY OF ACOUSTIC PRESSURE

The peak acoustic pressure near the ground surface has been observed to decay as the square of distance from the launch pad [7]. Spectral analysis which involves fast Fourier transform of the acoustic pressure data collected at locations during the PSLVD3 launch at SHAR is done by using the STAR software package [11]. The power spectral densities of acoustic pressures measured at various locations are compared and it is found that these spectral values also decay with distance from the launch pad in addition to their variation with frequency. Hence, an empirical expression has been derived for the power spectral density of acoustic pressure as a function of frequency and distance from the launch pad:

$$S_{p_x}(n, D) = P_x^2(1/27(1 + n))^{4/3} \quad (3)$$

where

$$P_x = P_{ref}(D_{ref}/D_x)^2, \quad (4)$$

$S_{p_x}(n, D)$  is the power spectral density of acoustic pressure at frequency  $n$ , at a distance  $D_x$  from the launch pad,  $P_x$  the peak acoustic pressure at distance  $D_x$  from the launch pad,  $n$  the frequency (Hz) and  $P_{ref}$  the peak acoustic pressure measured at reference point at a distance  $D_{ref}$  from the launch pad.

In the above formulation, a reference point to be selected is the pressure transducer location which is at the shortest distance from the launch pad. For PSLV-D3 launch data, the reference pressure gauge location is at a distance of 25 m from the launch pad. Figure 6 shows the power spectral densities of acoustic pressures measured during the PSLV-D3 launch and the respective values obtained using the empirical formulation developed as above, i.e., using equations (3) and (4). The PSD values for acoustic pressures can be seen matching very well with the PSD values based on measured acoustic pressure data for distances  $x = 25$  m (1), 37 m (4), 87 m (3), 83 m (2), 60 m (5), 200 m (7), 200 m (8) from the launch pad. In the launch complex, the sound pressure levels are instrumented at eight places and the numbers in parenthesis above indicate the location of these gauges as shown in Figure 1. The sound pressure level gauge at  $x = 85$  m(6) is shielded by a building from receiving the acoustic emission from the launch pad. Hence, the PSD values predicted show deviations from the PSD values based on measured data.

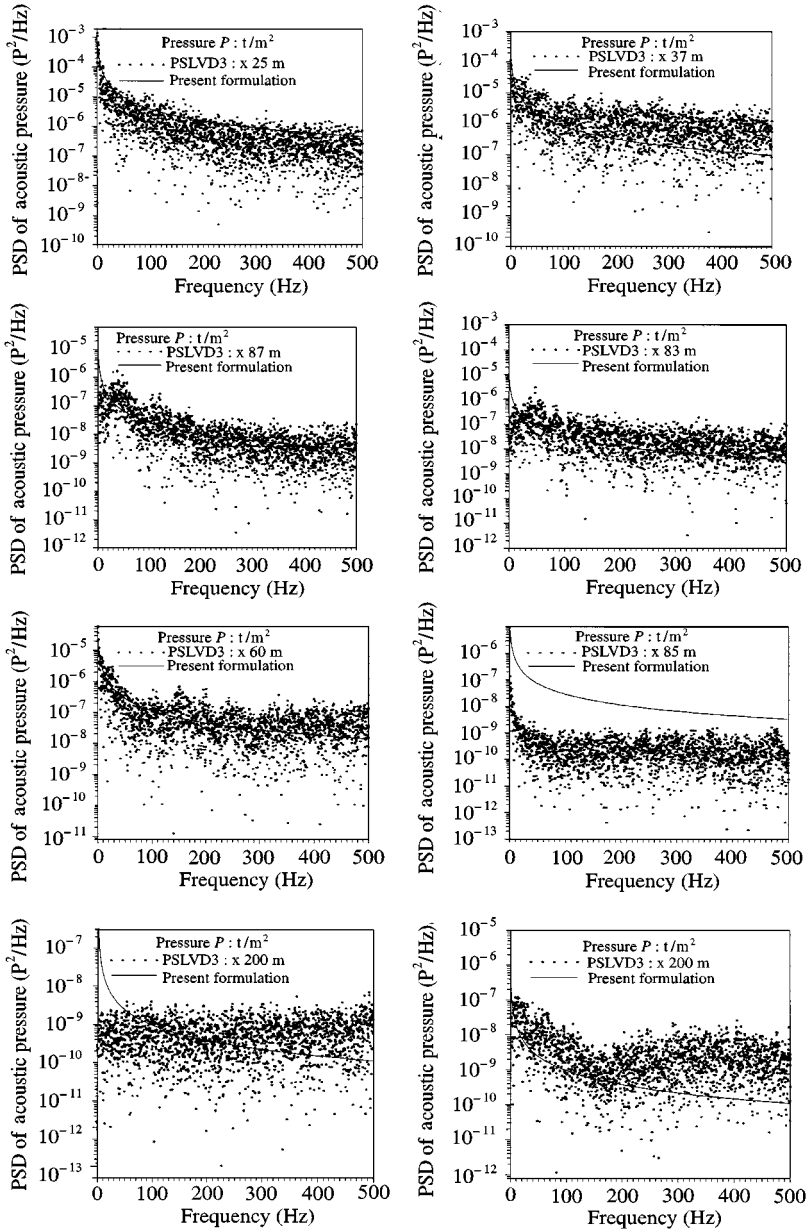


Figure 6. Comparison of measured and predicted acoustic pressure PSDs for PSLVD3 launch environment.

Figure 7 shows the power spectral densities of acoustic pressures from three pressure transducers measures at KSC, U.S.A., compared with those obtained using the present empirical formulation corresponding to KSC launch complex details.

As the developed power spectral density formulation is predicting very well the power spectral density of acoustic pressures for PSLV-D3 launch data, and also

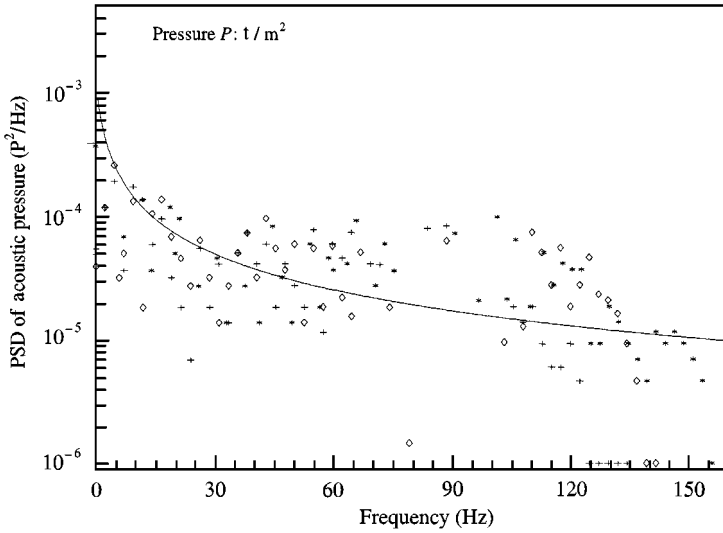


Figure 7. Comparison of measured and predicted acoustic pressure power spectral densities for KSC launch environment. ----, KSRPA001A; + + + +, KSRPA002A; ◊◊◊◊; KSRPA003A; —, present formulation.

KSC launch data, this formulation is used in the analytical routines of ACOUP for computing the PSD of acoustic pressures required for computing the acoustic response.

### 3.2. RESPONSE COMPUTATION

From the contributions of acoustic force from all elements meeting at a node, the global force vector of power spectral densities is assembled. At a typical node  $j$ , where  $m$  elements meet, the global vector of power spectral densities of force is

$$S_{fj}(n) = \sum S_{fm}(n). \tag{5}$$

The spectral analysis of structures for any random loading begins with the determination of natural frequencies and modal vectors by solving the generalized eigenvalue problem.

$$K\phi_i = \lambda_i M\phi_i, \tag{6}$$

where  $K$  is the stiffness matrix of structure,  $M$  the matrix of structure,  $\lambda_i$  the  $i$ th eigenvalue  $= \omega_i^2$ ,  $\omega_i = i$ th natural frequency (rad/s)  $= 2\pi n_i$ ,  $n_i$  the natural frequency (Hz) and  $\phi_i$  the  $i$ th mode shape.

The global force PSD vector  $S_f(n)$  is transformed into modal co-ordinates by the operation

$$S'_f(n) = \phi_i^T S_f(n) \phi_i. \tag{7}$$

The  $i$ th modal response of the structure is then obtained as

$$S'_x(n) = S'_{f_i}(n) / [\omega_i^4 ((1 - (n/n_i))^2 + (2\xi_i(n/n_i))^2)], \tag{8}$$

where  $\xi_i$  is the  $i$ th modal damping factor.



The global response vector of the structure is then obtained as

$$S_x(n) = \phi_i S'_x(n) \phi_i^T. \quad (9)$$

The r.m.s. value of the response along any particular degree of freedom,  $j$ , is obtained as

$$\sigma_{xj} = \left[ \int_0^\infty S_{xj}(n) dn \right]^{1/2}. \quad (10)$$

The peak spectral value of response occurring at a frequency,  $n$ , is obtained as

$$X_j = \sqrt{S_{xj}(n')n'}. \quad (11)$$

#### 4. COMPUTATION OF ACOUSTIC RESPONSE USING 'ACOUP'

Acoustic responses are estimated for the roof panel and wall panel of Checkout Terminal Room (CTR) building at SHAR launch complex and the roof panel and wall panel of Switching Station Enclosure (SSE) building at Kennedy Space Centre (KSC), U.S.A., using ACOUP. Details about modelling of these panels and computed acoustic response are given below.

##### 4.1. CHECK OUT TERMINAL (CTR) BUILDING WALL PANEL

The concrete wall panel of the checkout terminal room building which is located on the east side of the building facing the launch pad is analysed. The size of the panel is  $4.1 \times 2.8$  m and has a thickness of 0.3 m. The panel is discretized into a finite element mesh consisting of 117 nodes and 192 triangular elements. The co-ordinates of the reference point where peak acoustic pressure is measured (which is at a distance of 25 m from the source) with respect to the panel co-ordinate axes are (8.20, -1.70, 0.00). The co-ordinates of the source, i.e., launch pad from where the acoustic emission takes place during a launch are (29.76, -3.70, 12.65). The reference pressure is taken as  $0.0385 \text{ kg/cm}^2$ , which is the peak pressure recorded at the reference distance.

Analytically, the response is computed by assuming the bottom edge of the panel as fixed and for all other edges only the rotations about the  $x$ - and  $y$ -axis are allowed. During the field investigations conducted by SERC, during the PSLV-D3 launch, this wall panel was instrumented with accelerometer V1 and strain gauges S3 and S4. Figure 8 shows the power spectral density plot of acceleration measured by V1. The maximum response recorded experimentally and the response that is obtained analytically are tabulated in Tables 1 and 2 respectively. Figure 9 shows pictorially the location of the building wall panel and its distance from the launch pad.

##### 4.2. CHECK OUT TERMINAL ROOM (CTR) BUILDING ROOF PANEL

The concrete roof panel of the checkout terminal room building, which is located on the east side of the building nearer to the launch pad, is analysed. The size of the

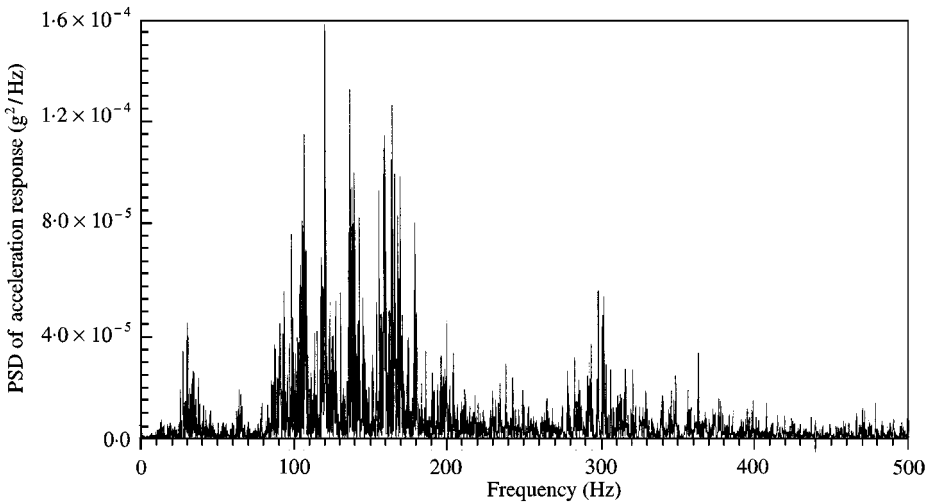


Figure 8. Acceleration response measured at the centre of wall panel of CTR building.

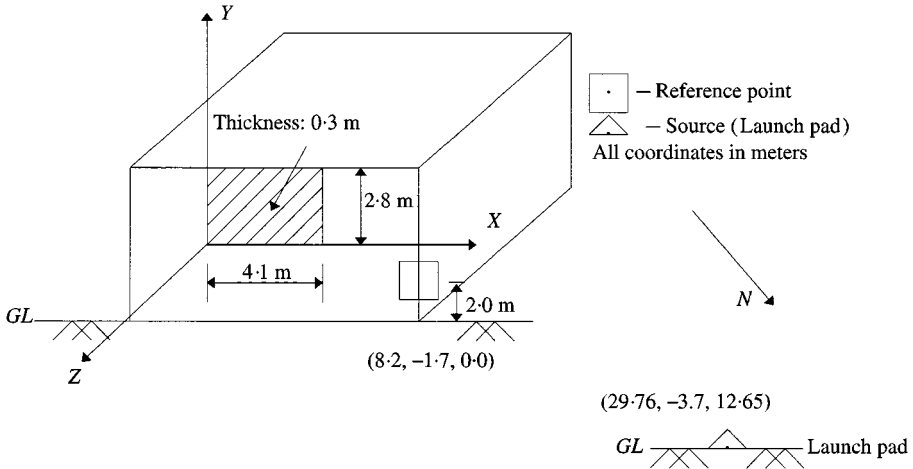


Figure 9. Details of wall panel of CTR building.

panel is  $12.3 \times 4.92$  m. The panel is discretized into a mesh with 65 nodes and 96 triangular elements. The co-ordinates of the reference point with respect to the panel co-ordinate axes are  $(12.30, -5.69, -6.50)$ . The co-ordinates of the acoustic source are  $(29.76, -3.70, 12.65)$  and the reference pressure is taken as  $0.0385 \text{ kg/cm}^2$ , which is the peak pressure recorded at the reference point.

The theoretical response is computed by assuming the roof panel edges, which are resting on beams and walls as fixed, i.e., east side longer edge and two shorter edges, and only the vertical displacement is allowed on the west side longer edge which is resting on a beam. This panel is instrumented with accelerometer V4 during the PSLV-D3 launch. Figure 10 shows the power spectral density plot of acceleration measured by V4.

TABLE 1  
*Experimental results*

No.	Case study	Launch	PSD of acceleration ( $\text{g}^2/\text{Hz}$ )	Peak displacement (mm)	Peak frequency (Hz)
1	CTR wall panel (India)	PSLV-D3 (V1)	$1.32 \times 10^{-4}$	0.00221	121
2	CTR roof panel (India)	PSLV-D3 (V4)	$8.51 \times 10^{-5}$	0.1014	8
3	SSE wall panel (U.S.A.)	STS-43	$3.45 \times 10^{-2}$	0.3930	24
		STS-48	$2.97 \times 10^{-2}$	0.3643	24
4	SSE roof panel (U.S.A.)	STS-38	$1.212 \times 10^{-1}$	10.56	4
		STS-39	$1.589 \times 10^{-1}$	12.43	4
		STS-43	$1.266 \times 10^{-1}$	11.05	4
		STS-48	$1.021 \times 10^{-1}$	9.91	4

TABLE 2  
*Analytical results*

No.	Case study	Software	PSD of acceleration ( $\text{g}^2/\text{Hz}$ )	Damping	Peak displacement (mm)	Peak frequency (Hz)
1	CTR wall panel (India)	ACOUP	$1.257 \times 10^{-4}$	0.01	0.00228	114
2	CTR roof panel (India)	ACOUP	$7.52 \times 10^{-4}$	0.02	0.13010	14
3	SSE wall panel (U.S.A.)	ACOUP	$1.49 \times 10^{-2}$	0.005	0.25800	24
		NASTRAN [1]	$2.98 \times 10^{-2}$	0.030	5.36000	4
4	SSE roof panel (U.S.A.)	ACOUP	$1.810 \times 10^{-2}$	0.020	13.20700	4.0
		NASTRAN [1]	$1.292 \times 10^{-1}$	0.030	23.59000	2.3

The maximum response obtained experimentally and the response that is obtained analytically are tabulated in Tables 1 and 2 respectively. Figure 11 shows pictorially the location of building roof panel and its distance from the launch pad.

#### 4.3. KENNEDY SPACE CENTRE—SWITCHING STATION ENCLOSURE BUILDING SOUTH WALL PANEL

The south wall panel of the switching station enclosure building at KSC is analysed. The size of the panel is  $5.4 \times 2.4$  m and the thickness is 0.075 m. The wall panel is of double tee cross-section as shown in Figure 3. The panel is discretized

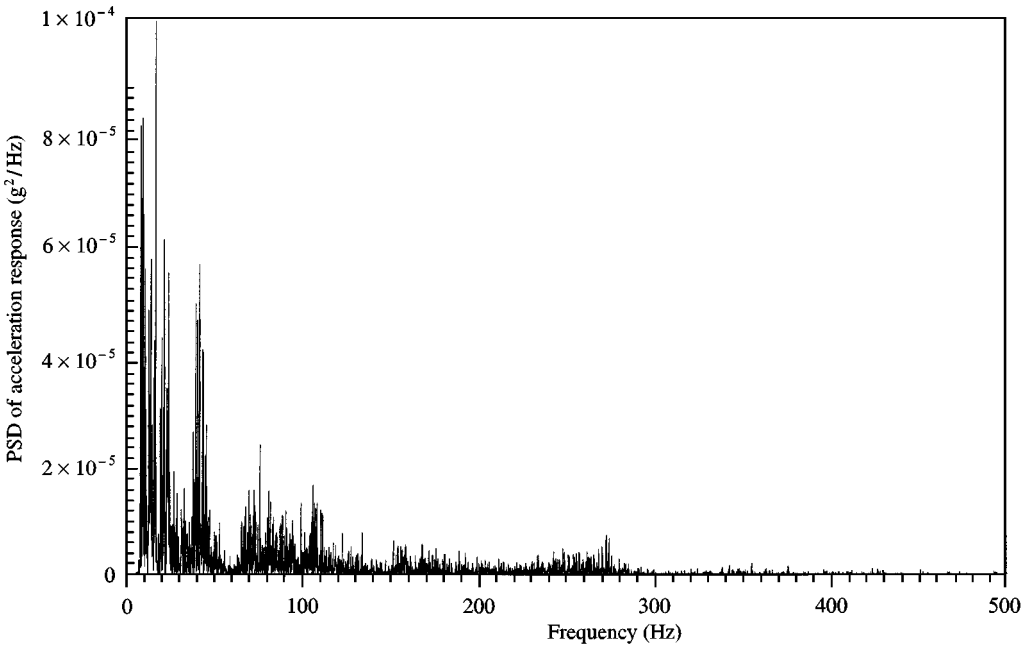


Figure 10. Acceleration response measured at the centre of roof panel of CTR building.

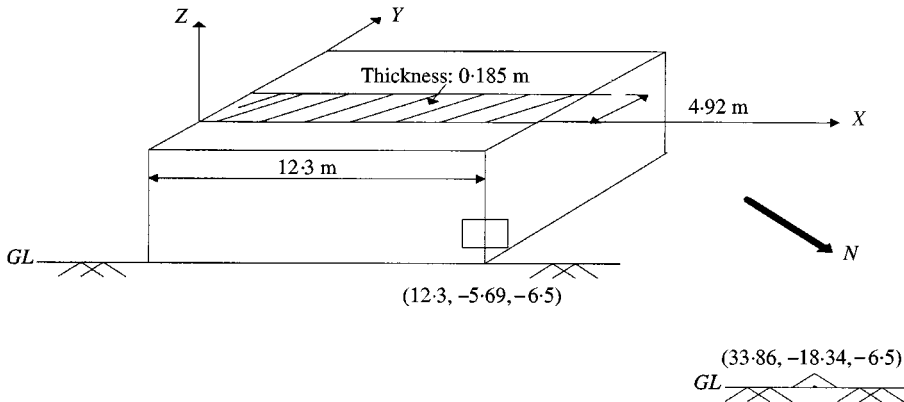


Figure 11. Details of roof panel of CTR building.

into a mesh consisting of 171 nodes and 288 triangular elements for the flange portion of the wall and 18 beam elements each for the two web portions. The co-ordinates of the reference point with respect to the panel co-ordinate axes are (1.20, 5.40, - 5.40). The co-ordinates of the source are ( - 105.00, 0.00, - 10.80) and the reference pressure is taken as 0.0375 kg/cm<sup>2</sup> which is the maximum acoustic pressure measured on the roof of the SSE building.

Analytically the response is obtained by assuming that the bottom edge is fixed; only rotations are allowed on the sides and rotations and translations are allowed

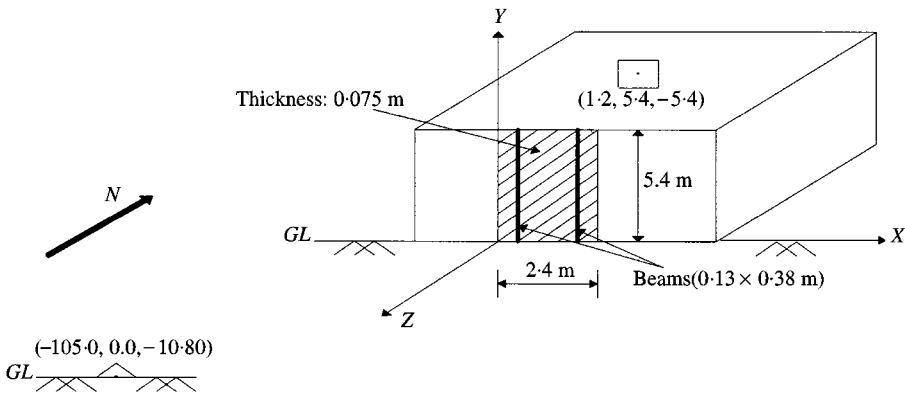


Figure 12. Details of south wall panel of KSC-SSE building.

for the top edge. The panel was instrumented with the transducer KSRDA016A at the centre and the structural response was recorded during the launches STS-43 and STS-48. The response recorded by the transducer and the analytically obtained response values are tabulated in Tables 1 and 2 respectively. Figure 12 shows pictorially the location of the building wall panel and its distance from the launch pad.

#### 4.4. KENNEDY SPACE CENTRE—SWITCHING STATION ENCLOSURE ROOF PANEL

The roof panel of the switching station enclosure building at KSC is analysed. The size of the panel is  $2.4 \times 21.6$  m and has a thickness of 0.075 m. The roof panel is of double tee cross-section as shown in Figure 3. The panel is discretized into a mesh consisting of 185 nodes and 288 triangular elements for the flange portion and 36 beam elements each for the two web portions. The co-ordinates of the reference point with respect to panel co-ordinate axes are (1.2, 10.8, 0.0). The co-ordinates of the source are  $(-105.0, 10.8, 5.4)$  and the recorded reference pressure is taken as  $0.0375 \text{ kg/cm}^2$ , which is the maximum acoustic pressure measured at the location of SSE building.

Analytically the response is obtained by assuming the panel as simply supported on the shorter side edges and the longer edges free. The panel was instrumented with the transducer KSRDA008A at the centre and the structural response was recorded during four launches at KSC, USA. The maximum response of the panel obtained experimentally and the maximum analytically computed response are tabulated in Tables 1 and 2 respectively. Figure 13 shows pictorially the location of building roof panel and its distance from the launch pad.

## 5. DISCUSSIONS

The damping factors, assumed in the theoretical analyses reported here, are based on past experience in experimental research on reinforced concrete

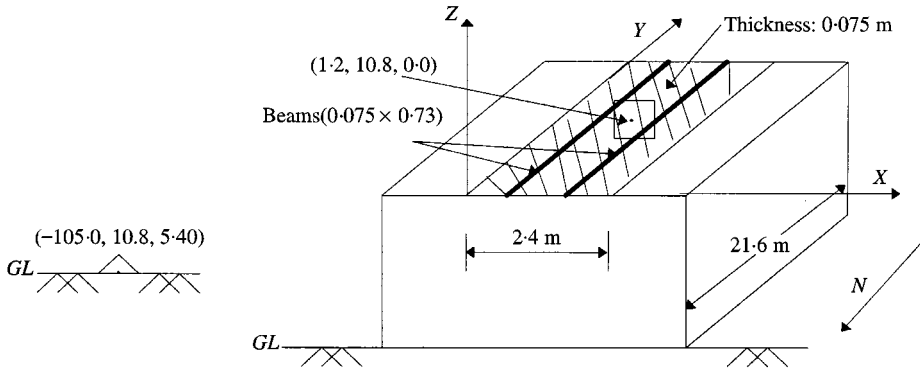


Figure 13. Details of roof panel of KSC-SSE building.

structures. These values, varying from 0.5 to 2%, are adjusted to improve the degree of correlation with the measured responses. In the case of the CTR building wall panel, a damping factor of 1% is assumed and it is considered the same for all modes. The predicted displacement at the centre of the panel is 0.00228 mm at 114 Hz, and the measured peak displacement is 0.00221 mm at 107 Hz. The peak displacement and the frequency at which that response occurred are fairly close to the experimental results. This can also be seen from the typical power spectral density plot for acceleration response, shown in Figures 14(a) and (b) respectively.

The measured acceleration response spectra show the complete range of natural frequencies of the entire building whereas the present analysis will show only the natural frequencies of only the building component in study.

Hence, the natural frequencies and peak response values of the building component from the present analysis are compared only with the experimentally measured response from the instrumentation located on that component only.

For the CTR building roof panel, the predicted displacement at the centre of the panel is 0.1301 mm at 14 Hz (damping: 2%) and the measured peak displacement is 0.10140 mm at 8 Hz. The predicted and the measured peak displacements are very close but the frequency at which the responses occurred differed.

The peak response computed for the KSC-SSE building wall panel is 0.258 mm at 24 Hz and the measured peak response value is 0.419 mm at 24 Hz. The frequency at which the peak response occurred is the same, but the peak response is less than the measured value. For this panel the computed response by Lin [6] is 5.36 mm at 4 Hz, which are more deviated from the measured values.

The peak response computed for the KSC-SSE building roof panel is 11.83 mm at 4 Hz (damping, 2%) and the measured peak response value is 12.43 mm at 4 Hz for the STS-39 launch. The peak displacement and the frequency at which the peak response occurred are very close to those measured. For this panel, the computed response by Lin [6] is 25.36 mm at 2.3 Hz which are more deviated from the measured values.

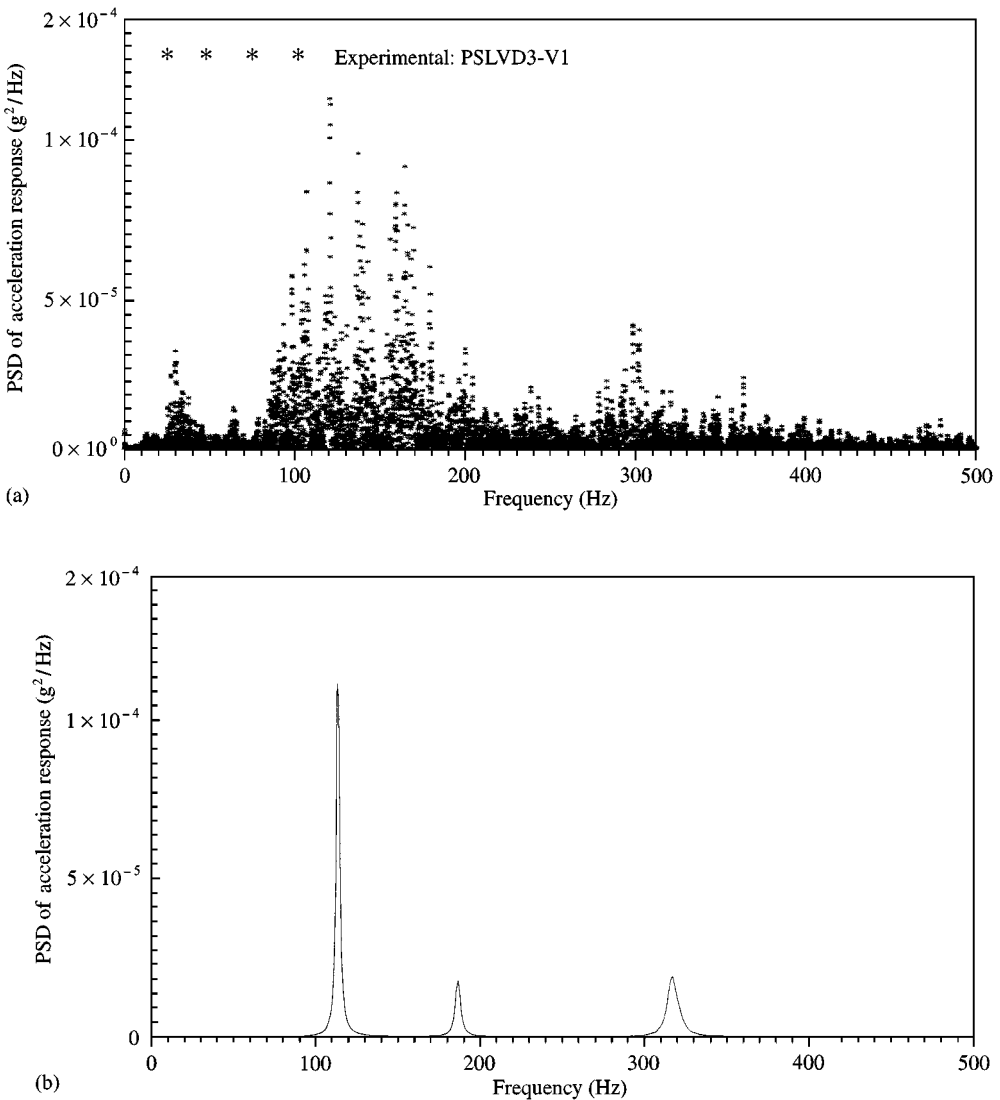


Figure 14. (a) Measured acceleration response for wall panel of CTR building; (b) Computed acceleration response for wall panel of CTR building.

## 6. CONCLUSIONS

1. The power spectral density of acoustic pressure values based on the present empirical formulation and the same from the measured data match very well, indicating the applicability of the PSD formulation to different launch environments.
2. The PSD formulation is based on the spatial and frequency variation of acoustic pressure, and hence can be used for any building in a launch complex, located at a distance from the launch pad.
3. The computed acoustic responses of building components using ACOUP match very well with the measured responses. This validates the software

routines developed and indicates their usability for predicting the acoustic response of structures and structural components in a launch environment.

4. Due to the advances in rocket technology and the use of very powerful space vehicles for launching greater pay loads, the buildings in the space craft launch complex may experience very high acoustic pressures. Hence, using the present methodology (ACOUP), the acoustic responses of structures can be predicted and remedial measures can be taken if necessary.

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